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Top Quark Physics at the High Luminosity LHC

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A summary of the prospects for top-quark physics at the High Luminosity LHC is given.

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1 Introduction

After Run 2 of the LHC the accelerator will undergo a significant upgrade phase to be able to deliver to the experiments a total integrated luminosity of 3 ab^{-1} at a centre-of-mass energy of 14 TeV. The ATLAS and CMS collaborations will also upgrade their detectors[1, 2] in order to profit from the large total luminosity, while coping with the increased number of pile-up interactions. During this “High Luminosity” phase the LHC (HL-LHC) will become effectively a top-quark factory with a total number of ~ 3 billion top-quark pairs produced and ~ 1 billion produced singly. In this summary we report the most important measurements that could be achieved during the HL-LHC and the latest extrapolations on their uncertainties. Precision top-quark physics is one of the main tools to probe for new physics beyond the Standard Model (SM) in an indirect way, if no clear discovery is made during Run 2 of the LHC. Lastly we consider how top quarks produced in decay of new exotic particles can increase the spectrum of direct searches for phenomena beyond the SM.

2 The high luminosity LHC programme

The high luminosity programme is scheduled to start in 2024 with a long shutdown, called LS3, during which the machine and the detectors will be upgraded to function at a luminosity of $5 (7.5) \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to an average pile-up of $\langle \mu \rangle = 140 (200)$. The plan is to collect a total integrated luminosity of 3 ab^{-1} by the end of the HL-LHC programme. Currently the experiments are in the process of drafting TDR documents, describing the upgraded detector that should allow to keep or enhance the Run 2 performance for physics, even in the more complicated high pile-up environment. Both detectors will undergo quite similar upgrades: the tracker and vertexing detectors to cope with the larger pile-up and radiation and to allow triggering on tracks at L1 of the trigger system; the electronics of the calorimeters; a refurbishing and extension of the muon system and their electronics to increase acceptance and trigger capabilities; and a new trigger and DAQ to cope with the high rates. For the case of CMS the project includes also the replacement of the forward calorimeter with a high-granularity option that in conjunction with the increased tracker efficiency at large η should improve reconstruction of forward physics objects and help with the overall pile-up mitigation and missing energy resolution. The possibility of a fast-timing layer is also being considered by both experiments for the mitigation of pile-up and improvement in event vertex reconstruction. Several studies have been already performed [3, 4, 5, 6, 7, 8], that show how the upgraded detector maintains or extends the current capabilities for physics measurements.

3 Challenges of upgrade physics studies

The process of evaluating performance of future detectors and physics potential is always complicated. In the case of the HL-LHC the main technical challenges are the simulation of the detector and large pile-up, which requires significant computing resources on one hand, while the estimate of the background from detector effects or from the fake contributions is by definition difficult to estimate. Most of the systematic uncertainties that are evaluated with data are assumed to get reduced, scaling with the larger datasets available. In the end the precision of the results will depend on the progress of the theoretical calculations in 15 years from now. In order to extract the numbers presented here some choices have been taken by the two experiments. Concerning the simulation of signal and background events, both ATLAS and CMS have chosen the path of a fast simulation that uses a simplified description of the detector and a parameterisation of the response [9].

4 Top-quark mass

Studies of the uncertainties on the top quark mass, extrapolated by the CMS collaboration from measurements with 19.7fb^{-1} of data at 8 TeV, have been updated [10]. Several methods are considered that suffer from different theoretical systematic uncertainties, related to the definition of the top-quark mass. Different assumptions enter the calculation of the updated uncertainties. It is assumed that the pile-up mitigation techniques will be adequate to keep the effects under control, in particular no degradation of the jet resolution is expected. It is further assumed that the loss of efficiency due to increased thresholds will be compensated by the higher cross section at 14 TeV. The statistical uncertainty is expected to scale with the square root of the collected integrated luminosity. This might be a conservative assumption as the increased acceptance of the upgraded detector in the forward region is not taken into account. The conclusion is that with 3ab^{-1} of data all the measurement will be systematics limited and especially by theoretical modelling uncertainties. Conventional methods, which would remain the most precise ones, are expected to yield an ultimate relative uncertainty of 0.1%. The new extrapolations are shown in Fig.1 (left).

5 FCNC in top-quark decays

In the framework of the SM, top-quark flavor changing neutral currents (FCNC) are highly suppressed. Predicted branching fractions for processes like $t \rightarrow \gamma u(c)$ and $t \rightarrow Zu(c)$ range from $10^{-16}(10^{-14})$ to $10^{-17}(10^{-14})$. These values are several orders of magnitude below the sensitivity of current and planned experiments. However, these branching ratios are enhanced in several extensions of the SM, and any observation

of these rare transitions would be a clear signal for a new physics effect. Two studies have been updated to evaluate the sensitivity of the upgraded ATLAS and CMS detectors during the HL-LHC run. The first one by ATLAS [11] concerns the search for FCNC in events with pair-produced top quarks, decaying to final states with three leptons, two of which compatible with a leptonic Z boson decay, at least one b -tagged jet, and at least one other non-tagged jet. This selection allows to extract limits on the process $t \rightarrow Zq$. The sensitivity increases by factors of two to six considering different scenarios for the systematics uncertainties, reaching values between 8 and 20×10^{-5} in the more optimistic configuration. A second search for the case where one of the two top quarks decays via $t \rightarrow Hq$ with $H \rightarrow b\bar{b}$ is performed requiring events with large jet multiplicity and at least two b -tagged jets, see Fig. 1 (right). For this analysis the signal extraction is more challenging and a multivariate approach is employed, to obtain a final sensitivity around 10^{-4} , which is twenty times better than previous extrapolations. The last analysis considered is the search for events where a single top quark is produced in association with a photon via an anomalous FCNC vertex $tq\gamma$. The event selection requires the presence of a top quark decaying in the leptonic channel and one isolated high E_T photon, well separated from the top decay products. Also in this case the sensitivity increases by a factor between three and ten (depending on the assumptions on the systematic uncertainties) obtaining limits on $B(t \rightarrow u + \gamma)(B(t \rightarrow c + \gamma))$ of $2.7 \times 10^{-5}(2.0 \times 10^{-4})$. It is clear that the study of FCNC has a large potential at the HL-LHC due to the very large statistics of top quarks anticipated. Possibly, analyses re-optimized to profit of the full potential of the new detector would improve even more that reach.

6 Top quarks as portal to new physics

The top quark is a natural candidate, due to its large mass, to connect us to potential new physics signatures. The analyses can profit of clean selections that push the phase space normally examined by traditional searches. In the case of SUSY models, for instance, measuring precisely properties of the top system, such as spin correlations, has allowed to probe the kinematically difficult corner for the stop pair production, close to the top-quark mass [12]. In the case of a mass splitting between the gluino and the LSP close to twice the top-quark mass, the search for a four-top final state can explore the gluino pair production. These kind of analyses, that are being performed in Run 2 [13, 14], will profit from a larger integrated luminosity. The improvement in the reconstruction of top quarks as boosted objects and the large HL-LHC dataset will also help to push the sensitivity up to 4 TeV for the search for heavy bosons such as $Z' \rightarrow t\bar{t}$ or $W' \rightarrow tb$ [10, 15], even if a machine with larger energy would perform better. Finally, having a larger dataset and restricting the selection to very boosted top-quark events will allow to improve the sensitivity to

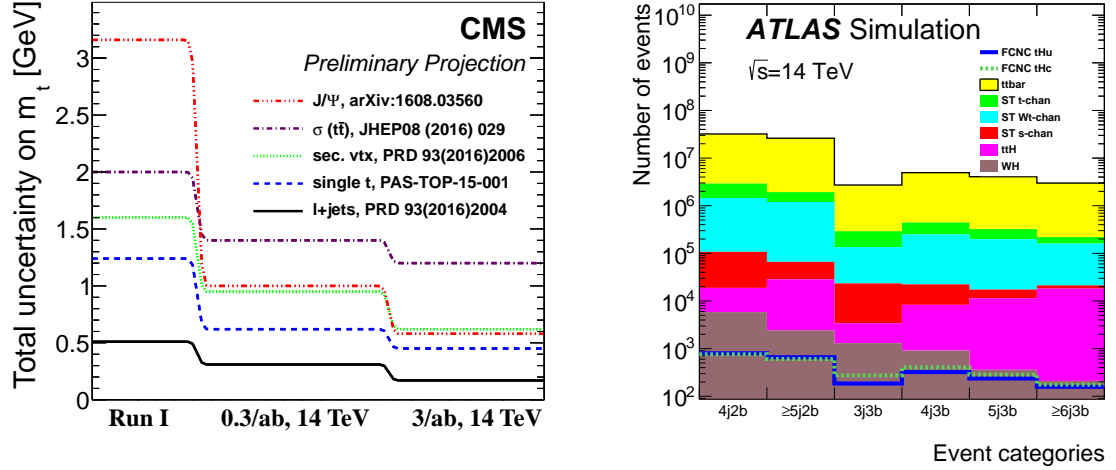


Figure 1: (Left) Total top-quark mass (m_t) uncertainty obtained with different measurement methods at present and their projections to the HL-LHC[10]. The projections are based on measurement obtained with the CMS detector during Run 1 of the LHC.

(Right) Selected signal and background events in the six analysis categories for the reference ATLAS detector upgrade layout[11]. The signal $t \rightarrow Hu$ and $t \rightarrow Hc$ event numbers correspond to a FCNC branching ratio of 2.67×10^{-5} .

anomalous ttZ axial and vector couplings [17], gtt chromo-magnetic moments [18] or top asymmetries (A_C, A_{FB}) [19].

7 Summary and conclusions

The potential opportunities for top-quark physics offered by the HL-LHC are being explored again, profiting from the Run 2 data at 13 TeV. The extrapolation to new detectors and harsher running conditions is not trivial, and the work is just starting. It is clear that top physics is a major item for the physics programme of the Phase 2: in terms of advancing the precision of the SM measurement, in finding deviations due to new physics effects or looking for new particles decaying to top quarks. The larger datasets of top-quark pairs and single top will allow to perform new analyses that profit of rare final states and extreme kinematical phase space.

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